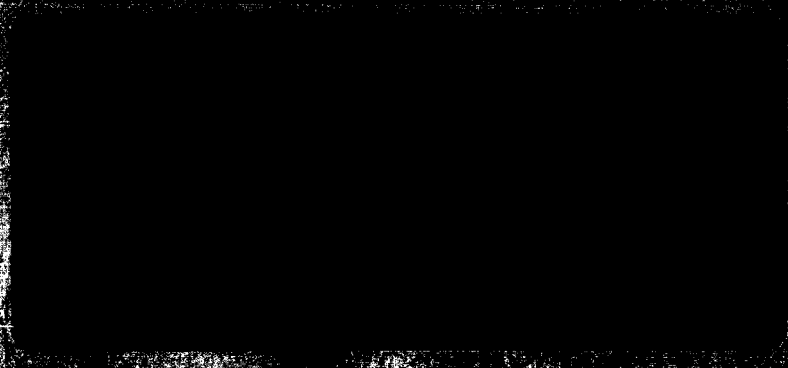


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[A. I. Rezanov]

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THERMAL AND THERMOELECTRIC PROPERTIES OF FERROMAGNETIC METALS¹

A. I. Rezanov

The model developed by S. V. Vonsovskii (Ref. 1) for the interacting inner and outer electrons of a ferromagnetic metal has shed light on the anomalous temperature dependence exhibited by the conductivity of ferromagnets near the Curie temperature. An essential feature of Vonsovskii's theory is that it allows for electrostatic exchange coupling between inner electrons (3*d*-shells of isolated atoms) and outer electrons (4*s*-shells) in the crystal lattice.

The outer *s*-electrons are moving not only in the lattice ion field but also in the field of the inner *d*-electrons. Consequently, their dynamic characteristics (effective mass, time of traversal of one mean free path, etc.) depend on the state of the inner electrons, i.e., in ferromagnets primarily on their resultant magnetization. It may be said, to a first approximation, that there is a rather quasi-magnetic exchange coupling field acting on the *s*-electrons. As a result of this field the outer electrons are divided into two groups corresponding to the orientation of their intrinsic magnetic moments. The end result is that those properties of ferromagnetic metals which are attributable to the behavior of the outer electrons should display certain anomalies near the Curie point, where the spontaneous magnetization undergoes an abrupt variation with temperature.

The equation derived by Vonsovskii for the conductivity of ferromagnets near the Curie point is of the form

$$\sigma = \frac{A}{T} [1 + \gamma_{\sigma} (J_d + J_s)^2], \quad (1)$$

¹ Translated from *Doklady Akademii Nauk SSSR*, v. 82, no. 6, pp. 885-887, 1952.

where J_d and J_s are the values of the spontaneous magnetization for d - and s -electrons, γ_σ is a proportionality coefficient of the order of unity and contains the exchange coupling integrals of an s -electron with d -electrons near a single lattice site as well as for nearest neighbor sites. This equation is in agreement with the experimental results — especially with those obtained by Gerlach (Ref. 2).

Expressing the kinetic equation in the usual form and making use of the second approximation to calculate the integrals of antisymmetrical quantum statistics (Ref. 3), as well as the dependence of the effective mass, chemical potential, energy, and mean free path traversal time of the outer electrons on the spontaneous magnetization (Ref. 1), we derived equations for the Thomson coefficient and Peltier heat value. In all of the equations we separated the terms depending on J_d and J_s in the first approximation, for temperatures near the Curie point Θ , where the s -electrons are still greatly degenerate.²

The results of these calculations — which are all standard — are presented here. The thermal conductivity in this case has a form similar to Eq. (1):

$$\chi = B [1 + \gamma_\chi (J_d + J_s)^2], \quad (2)$$

where γ_χ is a proportionality coefficient equal to

$$\gamma_\chi = \frac{1}{(1 + k_1)^2} \left(k_1^2 + 4k_1 \frac{\beta'}{\beta} + \frac{\beta'^2}{\beta^2} \right);$$

k_1 is a constant of the order $10^{-1} - 1$ and connects the magnetizations J_d and J_s ($J_s = k_1 J_d$); $\beta' = \frac{1}{2} I_1$, $\beta = -b + \frac{1}{2} I_1$, where I_1 is the exchange integral of the s - and d -electrons of neighboring atoms, b is a quantity inversely proportional to the effective mass of an s -electron moving in the lattice ion field only.

For the case of low temperatures we obtained an equation for the temperature dependence of that part of the thermal conductivity which is specifically characteristic of the ferromagnetic state of the metal:

² The actual fact is that in typical ferromagnets the Curie point seldom exceeds 10^2 to 10^3 °K, whereas the degeneracy temperature of the conduction electron "gas" is equal in order of magnitude to 10^4 to 10^5 °K.

$$\chi \sim T^{-1}. \quad (3)$$

The thermal EMF of a pair of ferromagnetic conductors is found to be the following:

$$E = - \frac{\pi^2 k^2}{3e} \int_{T'}^{T''} \left\{ \left[\frac{\Lambda}{\zeta} (1 + \gamma_E (J_d + J_s)^2) \right]_1 - \left[\frac{\Lambda}{\zeta} (1 + \gamma_E (J_d + J_s)^2) \right]_2 \right\} T dT \quad (4)$$

(in the notation of Bethe and Sommerfeld (Ref. 3)). Here

$$\Lambda = 1 + \frac{1}{2} \frac{d \ln \bar{l}}{d \ln \bar{v}},$$

\bar{l} is the mean free path, \bar{v} is the mean electron velocity; $\zeta = \frac{1}{2} m \bar{v}^2$, m is the mass of an electron moving in the lattice ion field only.

From Eq. (4) we can obtain an empirical value of $-dE/dT$ for a thermocouple consisting of a ferromagnetic and a nonferromagnetic conductor (Ref. 4) near the Curie point:

$$- \frac{dE}{dT} = CT - \lambda T (\Theta - T). \quad (5)$$

At this point we have made use of the well-known thermodynamical equation $J_d + J_s = \alpha \sqrt{\Theta - T}$, and the constants C and λ are equal to

$$C = \frac{\pi^2 k^2}{3e} \left\{ \left(\frac{\Lambda}{\zeta} \right)_2 - \left(\frac{\Lambda}{\zeta} \right)_1 \right\}; \quad \lambda = \frac{\pi^2 k^2}{3e} \alpha \left(\frac{\Lambda}{\zeta} \right)_2 (\gamma_E)_2.$$

The Thomson coefficient was calculated by means of a thermodynamical equation relating it to the thermal EMF:

$$\mu_2 - \mu_1 = T \frac{d^2 E}{dT^2} = CT - \lambda T (\Theta - 2T) \quad (6)$$

(μ_2 is the Thomson coefficient for a ferromagnet).

The Peltier heat was also calculated by means of an analogous thermodynamical relation:

$$\Pi = T \frac{dE}{dT} = -CT^2 + \lambda T^2 (\Theta - T). \quad (7)$$

Equations (2), (5), and (6) are in qualitative agreement with the published results of experimental measurements (Ref. 4, 5). As far as we know, no attempt has been made to investigate experimentally the application of the Peltier effect to ferromagnets.

It is apparent from all of the derived equations that the temperature dependence of the ferromagnetic "perturbations" of the investigated variables is determined by the square of the spontaneous magnetization, while the temperature coefficients corresponding to each of these variables should exhibit a strong maximum near the Curie point.

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